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UAV-based LiDAR acquisition for the derivation of high-resolution forest and ground information

Felix Morsdorf[1], Christoph Eck[2], Carlo Zgraggen[2], Benedikt Imbach[2], Fabian D. Schneider[1], and Daniel Kükenbrink[1]

Abstract

Laser scanning of forested areas helps in analyzing and understanding various aspects of forest conditions, including distribution of plants and trees, height distribution of trees, tree density, size and volume of wood, as well as ground surface properties. However, laser scanning of forest areas is also very challenging for many reasons. The best time for scanning is before trees leaf out in the spring or after trees cast their leaves in autumn before snowfall so an unmanned aerial vehicle (UAV) laser scanner can penetrate the forest from the tops of the trees down to the ground surface. To receive highly accurate laser data and high point density, the flight planning must be adjusted judiciously. Flight planning will be even more complex in steep terrain where the UAV cannot operate at a constant altitude. This paper discusses a UAV-based 3D laser data recording — LiDAR scanning — of a forestry area with high accuracy and point cloud resolution. In addition, the point cloud of airborne laser scanning (ALS) is compared with local terrestrial laser-scanning (TLS) results. The forest area consists of mixed forests containing varying tree sizes and branch deformation. This paper summarizes our latest results in UAV-based LiDAR acquisition over a forest area to extract detailed forest and ground information and finds that UAV-based laser scanning (UAV-LS) is well suited for provision of both high-quality forest structural and terrain elevation information.

Introduction

The performance of unmanned aerial vehicle (UAV)-based laser scanning (UAV-LS) has shown remarkable results during the last decade in applications such as ground surface scanning, electrical powerline and vegetation scanning, and scanning of various ground objects (e.g., bridges, buildings, daylight mining areas, etc.). Various results have already been published (Guo et al., 2017; Sankey et al., 2017) and are well documented on websites (e.g., www.aeroscout.ch). Besides the mechanical and electrical integration of a laser scanner on the Aeroscout Scout B1-100 UAV helicopter, the flight performance of the UAV itself and the mission planning are challenging tasks in order to achieve accurate and homogeneous point clouds. In a forestry area, the demands on the point cloud density are even more challenging with up to 1000 pts/m^2. This high point density is required to allow identification of major tree branches and to determine tree diameters, tree diameter breast height, and accurate wood volume estimates. However, there are various challenges before, during, and after data recording, which are described in the following.

While the "Introduction" section of this paper describes the UAV system itself and the payload integration, the second section concentrates on the mission planning requirements. Mission execution is also described in the second section. The third section concentrates on data processing, combining trajectory data from the inertial measurement unit (IMU), the global positioning system (GPS), and the differential GPS station with recorded laser-scanning data. All data recording was performed on board in full resolution and downloaded after flight for further postprocessing. The fourth and fifth sections go into detail of forest and ground surface data analysis. The airborne laser scanning (ALS) data is also compared and supplemented with terrestrial laser-scanning (TLS) data. This TLS data was recorded in an accessible wilderness area with multiple positions. The last section of the paper gives some conclusions and also summarizes the major results.

UAV helicopter. The industrial Scout B1-100 UAV helicopter produced by Aeroscout GmbH, Switzerland, is a fuel-driven helicopter with a 100 ccm two-stroke fuel engine, providing a standard customer payload capacity of 18 kg and a flight endurance of 1.5 hours. The standard liftoff weight is 77 kg, including payload (18 kg), fuel (9 kg), flight control system (3 kg), batteries and data link (3 kg), and mechanics (44 kg). The Scout B1-100 UAV helicopter is equipped with a flight control system, which is powered with redundant batteries and is independent from the customer payload. Figure 1 shows the Scout B1-100 UAV helicopter during a laser-scanning flight over forestry area. The helicopter has a rotor diameter of 3.2 m and communicates with the ground control station (GCS) over several digital data links. Due to the classical helicopter configuration, the scanning performance and homogeneity of data collection in continuous forward flight are superior to multirotor aircraft, particularly under changing wind conditions (wind gusts, side wind, etc.). The flight performance of the helicopter is superior to experienced helicopter pilots, and automatic landing with submeter accuracy is possible.

LiDAR payload integration. The LiDAR payload (Figure 2) combines the OxTS xNAV550 IMU/GPS dual-GPS-antenna

Figure 1. The Scout B1-100 UAV with integrated laser-scanning payload during the flight above the forest area. The photograph was taken from a research observation tower.

[1]Remote Sensing Laboratories, University of Zürich.
[2]Aeroscout GmbH.

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navigation solution and the RIEGL VUX-1UAV laser scanner. The dual-GPS-antenna solution provides additional measurements of the roll and yaw angle of the payload and enables a static initialization of it. Time synchronization is based on GPS provided by the IMU/GPS unit. The data interface for both units has been realized with the Aeroscout Airborne Laser Scanning and Monitoring Integration (ALMI) software running on the GCS. The GCS communicates with the LiDAR payload using a wireless local area network data link. Before starting the engine of the helicopter for warm-up, the GPS reference station is initialized to determine the absolute GPS reference position. Afterward, the differential correction data is also stored at the GCS. Also before starting the helicopter engine, the LiDAR payload is initialized. After lift-off, a circular flight pattern does improve the angular precision of the IMU/GPS navigation unit during ascent.

Mission planning

UAV flight pattern. To achieve the high-resolution point cloud with more than 3200 pts/m^2, a line spacing of 20 m was chosen. Due to the steep terrain, the flight lines are flown automatically with a continuous climb rate along the mountain. To achieve optimal ground penetration of the laser scanner, the flight altitude above the tree canopy has been reduced to 20–30 m. With that, we are well within the range limits of the laser scanner, which is a few hundred meters for targets with a reflectivity of more than 30%. This flight pattern also allows having sideward laser-scanning data from the mountainside, which will further increase point density. Reducing the flight altitude was possible because there is a laser scan of the area from a previous flight, so the altitude of the trees was known to an accuracy of about 1 m. The overall flight pattern is shown in Figure 3. This screen shot was taken during the flight and shows the mission profile and the UAV status during the flight.

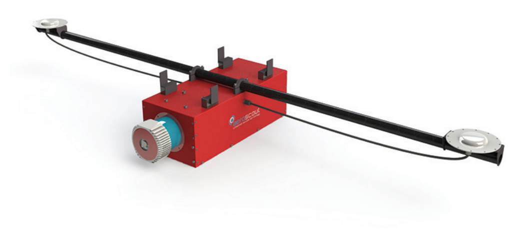

Figure 2. ALMI of a RIEGL VUX-1 laser scanner with the OxTS xNAV550 IMU/GPS dual-antenna navigation unit.

The cruising speed was set to 4 m/s based on the point density requirements. During turns, the cruising speed of the Scout B1-100 UAV helicopter was slightly reduced. The variation of the power requirements during the flight were well indicated by the throttle percentage. These power variations were due to wind conditions along the mountain area above the forest canopy and also due to wind turbulence while sunlight is warming the forest area in the morning. During the 30 minutes of the flight, the manual backup pilot remains in visual line of sight of the UAV helicopter as required by the Swiss Aviation Authority BAZL.

Configuration of the LiDAR payload. The RIEGL VUX-1UAV laser scanner has been set to an opening angle of 240° with a scanning rate at 550 kHz. Based on the nominal altitude above ground level of 80 m and a cruising speed of 4 m/s, this yields a point density of about 230 pts/m^2 for one scan line. Table 1 summarizes the settings of the LiDAR payload.

Data postprocessing

The processing of the laser data was done with the RIEGL software package RiPROCESS. The raw laser data is combined with the position and altitude data collected from the time-synchronized onboard IMU/GPS navigation sensor to get the 3D point cloud. Multiple flight lines with overlapping data allow for adjusting the laser data strips to improve the accuracy of their relative registration.

Figure 3. Mission planning and mission execution during the laser-scanning flight. Multiple flight lines with continuous climb rate allow the helicopter to follow the forest surface along the hilly area.

Trajectory processing. The IMU/GPS unit xNAV550 from Oxford Technical Solutions (OxTS) comes with its own processing software called RT Post-process. The software first downloads the recorded raw data from the unit and stores it in the specified folder. The recorded differential GPS file can be selected, together with the desired processing settings. For this flight, the trajectory was processed with a high GPS weighting and forward and backward calculations. After processing, the trajectory can be checked in RT-View, which is part of the processing software. It is then stored with the correct time representation; in this case, it is UTC time.

With that, the processing of the trajectory is finished, and it is ready to be combined with the laser-scanning data.

Laser-scan processing. As preparation for processing of the laser data, the raw laser data file is cut into sections with the help of the RIEGL tool rxpcutter. Every section covers one line of the flown trajectory, further referred to as a scan line. The processing of the laser-scanning data is done in the RIEGL software RiPROCESS. After creating a navigation and laser device, the trajectory and the scan lines are loaded into the software and are linked to the corresponding devices. Each scan line is linked to the trajectory, and with that the first processing of the laser data can be done.

The software imports all the data from the scan lines and uses the information from the trajectory to generate the georeferenced point cloud. During import of the scan lines, unwanted data was cut out to reduce the size of the scan lines, which helps to reduce computation time.

Figure 4. A part of the resulting point cloud after processing. Each scan line is represented with a different color.

Table 1. Summary of the laser-scanning mission.

Nominal flying height above ground	80 m
Nominal flying height above tree canopy	30 m
Spacing between flight lines	20 m
Scanning area	12 ha
Scanning rate	550 kHz
Opening angle	240°
Point density	230 points/m^2
Point spacing	0.06 m

The georeferenced point cloud can now be viewed inside the software either in 2D or in 3D. When looking at the point cloud at this stage of processing, an error up to 50 cm of how well the scan lines match on top of each other will be visible. One part of this error comes from the small angular displacement of the laser scanner in relation to the IMU/GPS unit; the other part comes from slightly changing GPS conditions during flight. These errors can be minimized with the help of the processing software.

In each scan line, so-called tie planes are searched. Tie planes are a number of points in a scan line that define a plane within the parameters set in the software. These can then be used to calculate the angle corrections of the laser scanner and the position and orientation adjustment of the scan lines themselves. To get the best results from these calculations, the tie planes should be well distributed with regards to their orientation. The flight area, for the most part, faces southwards, which made it difficult for the software to find enough tie planes in the east or west directions. Adjusting the search parameters resulted in a sufficient tie plane distribution to calculate the corrections of the scan data. With that, the scan lines could be adjusted so that the errors of how well the scan lines match on top of each other could be reduced to only a few centimeters.

After applying the corrections and recalculating the point cloud, the last step is to review the data, delete unwanted points from it such as flying particles in the air, and export it to the desired file format in the specified coordinate system.

Site and validation data

Site description. The Lägeren site is located at N47°28’49” and E8°21’05” at 682 m above sea level on the south slope of the Lägeren mountain, approximately 15 km northwest of Zürich. The south slope of the Lägeren marks the boundary of the Swiss Plateau, which is bordered by the Jura and the Alps. The western part is dominated by broad-leaved trees, mainly beech (Fagus sylvatica L.) and ash (Fraxinus excelsior L.). In the eastern part, beech and Norway spruce (Picea abies [L.] Karst.) are dominant. The forest has a relatively high diversity of species, ages, and diameters, and the ground cover consists of bare soil, boulders, and litter, while existing vegetation understory is characterized by a dense herb and shrub coverage. Average canopy height is 24.9 m, with a maximum of 49 m (numbers from ALS), and the stem density is 270 stems per hectare (derived from forest inventory). A core site of 300 m by 300 m has been subject to intensive ground and airborne measurement campaigns. Starting in 2010, the Lägeren site has been subject to intensive field campaigns, including single-tree forest inventory, spectroradiometric measurement, and TLS. Within the University of Zürich, the Lägeren is being used as a core test site for calibration, validation, and prototyping of remote-sensing methods, data, and products. Remote-sensing data acquired includes laser scanning and hyperspectral imaging data, and ranges from some millimeters (TLS) to 300 m (moderate resolution imaging spectroradiometer) in spatial resolution. Together with the field data, an excellent experimental setup for cross-, down-, and upscaling is provided.

Terrestrial and airborne laser data for cross comparison. Traditional ALS leaf-on and leaf-off data sets were acquired in 2014, using a RIEGL LMS-Q680i with a maximum scan angle of ±22 deg resulting in an average echo density of about 15 pts/m^2. The digital terrain model (DTM) was provided by the data supplier, and was created using the TerraScan software suite. During the same day of the UAV laser acquisition, a ground-based TLS survey was carried out using a RIEGL VZ1000 instrument. A total of 40 scans on 20 scan locations were taken in an area of roughly 60 m by 60 m in size. About 50 reflective targets were placed within the scene, to later be used for coregistration of the scans. The single scans were coregistered using RiSCAN PRO, and the UAV data were subsequently globally adjusted to the unified TLS point cloud. It should be noted that there was absolutely no wind on that day, greatly facilitating matching even of finer branches.

Results

Comparison with ALS. Figure 5 shows a qualitative and quantitative comparison of the UAV-LS point cloud (lower panels) with the operational ALS data set of Kanton Aargau (top panels), whose nominal point density was >4 echoes per meter square (actual for the subset shown is 15/m^2). The UAV-LS provides more than 3200 pts/m^2. Using an iterative closest point algorithm, we measured the UAV data to be shifted by [-1.67, -0.80, 1.21] m in x, y, z in respect to the geolocation of the ALS data. These shifts were corrected before applying to correlation analysis below.

The UAV data clearly shows much more details for trees and branches, including the structures comprising the flux tower. The ground information is also much denser. However, despite the large differences in point density, the vegetation profiles agree very well, having a correlation of 0.98 for all bins, dominated by the ground signal. When the ground returns are removed, the correlation drops to 0.88, which is still very high. Thus, the distribution of ground-corrected echo heights for ALS and UAV-LS is very comparable. The measurement accuracy of the UAV data is on the order of a couple of centimeters, as was established using the roof of a forest hut as a reference (Figure 6).

Comparison with TLS. Figure 7 shows a 10-deep transect of the merged TLS and UAV-LS point clouds. It is clearly visible that both methods deliver similar details on stems and branches but that UAV-LS has a higher coverage toward the top of the canopy, while TLS is stronger lower within the canopy. Stems are well defined in both data sets and larger branches are well resolved, making the data well suited for biomass estimations, e.g., by applying quantified structural models (Raumonen et al., 2013). Based on our findings and the results of the strip adjustment shown earlier, we think it is safe to say that UAV-LS is accurate enough for observing processes having more than 2–3 cm change signal (e.g., landslides or changing riverbeds), while, as with other

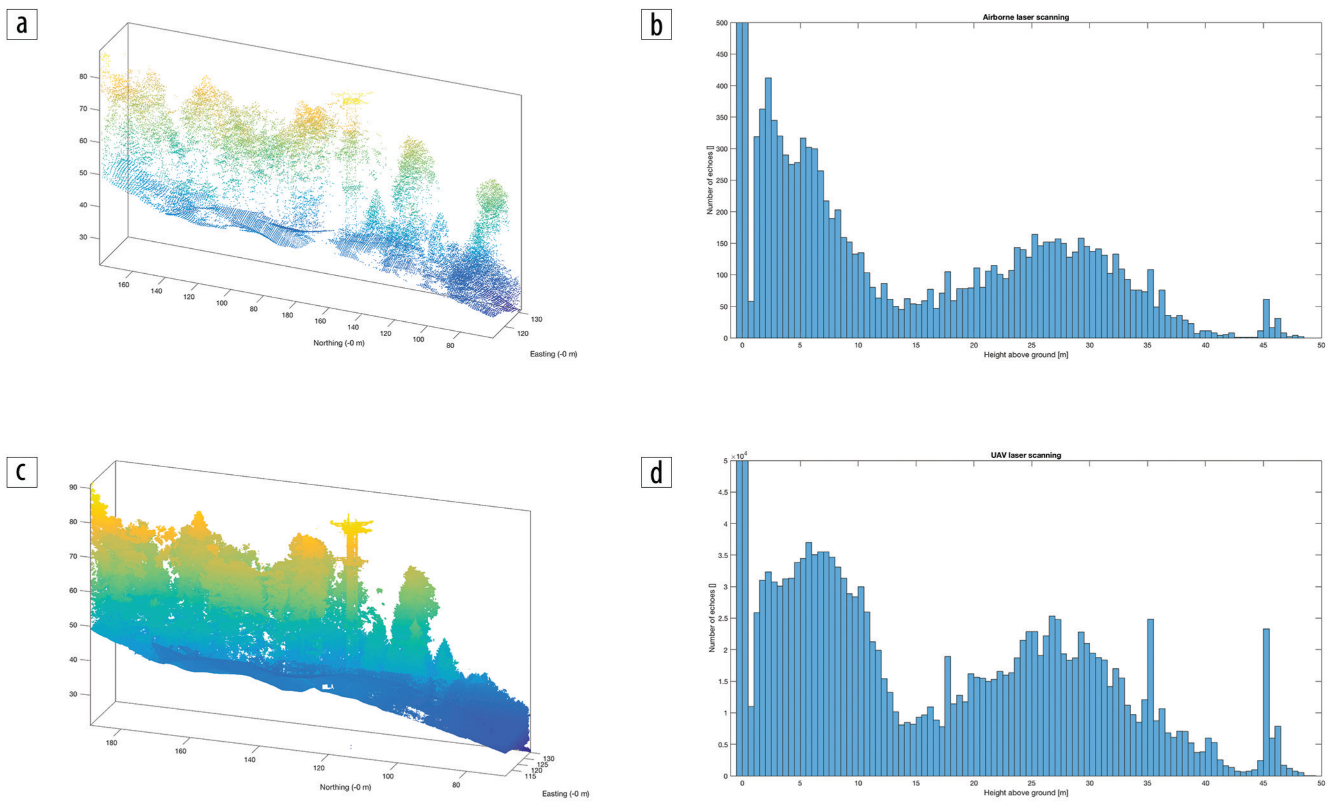

Figure 5. (a) ALS point cloud and (b) histograms of heights above ground from 2014 and (c) UAV based laser point cloud and (d) histogram from 2017 on a transect encompassing the flux tower (about 120 m by 20 m in size). The correlation between both vegetation height profiles is 0.98 with the ground returns and 0.88 just for vegetation echoes (h >= 1 m). Note that the tree to right has been removed between 2014 and 2017.

mobile laser-based methods, it is likely not accurate enough for processes with millimeter accuracy requirements, e.g., as subsidence.

Occlusion of lower canopy parts is still a problem in summer (leaf-on conditions), where only a limited number of returns can penetrate the canopy and reach the ground beneath the trees (leaf-on data not shown). It appears as if the smaller beam, lower-flying altitude, and large variation of incidence angles (compared to traditional ALS) only mitigates the occlusion to some extent, i.e., for all ground-focused campaigns, leaf-off still remains the survey condition of choice. A quantification of occlusion will be carried out using the approach from Kükenbrink et al. (2017).

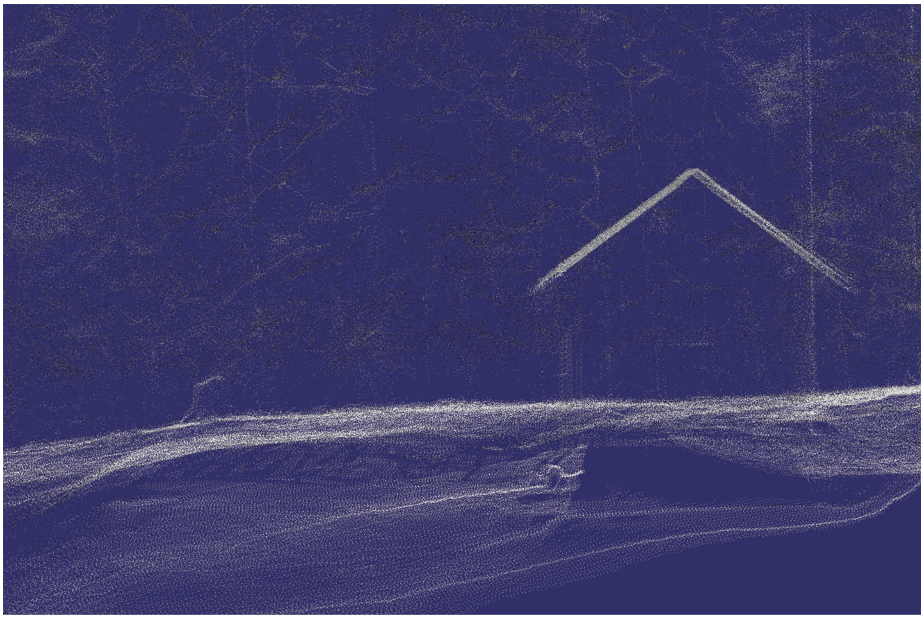

Figure 6. Detail view of the hut housing the flux tower electronics. Some small residuals of the strip adjustment are still visible as double outline along the roof, but these are on the order of a few centimeters.

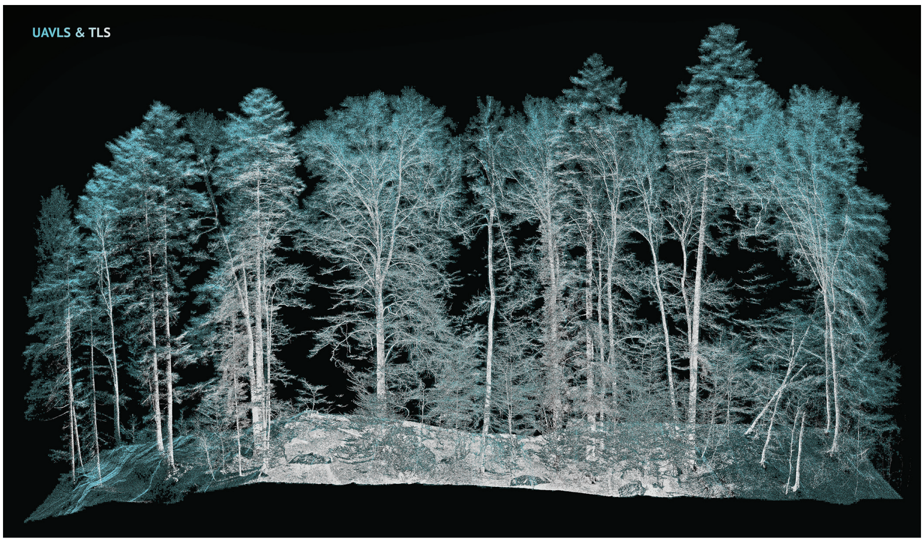

Figure 7. UAV-LS point cloud (cyan) and TLS point cloud (gray scale) from the recent survey.

Conclusion

Our aim in using UAV for laser scanning was to obtain accurate stem locations and terrain model over areas of several hectares. Considering the results, we have seen that UAV-LS data will be able to provide not only that, but also should provide stem and larger branch volumes, which is good news for forest ecology and inventory applications. Terrain elevation accuracy is high enough to facilitate monitoring of a large number of environmental processes. A large advantage of the UAV-LS compared to TLS is the more homogenous point distribution and the perspective from above, leading to more accurate canopy height estimations. The physical limits of occlusion, however, cannot be outsmarted using UAV-LS, so flying in leaf-off conditions is still favorable when DTM or wood volume are target variables. Summarizing, UAV-LS is the ideal tool to bridge the gap between ALS and TLS and it is a unique proposition for many local-scale forest canopy and surface elevation related observation tasks. TLE

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Corresponding author: felix.morsdorf@geo.uzh.ch

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